Overview

- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction
- Conclusion

Electro-Mechanical Heart Model

- From passive to active biomechanical model
- Triggered by ECG
- Adjusted from Image Measurements
- Advantages
  - more robust (can “beat” with partial image info)
  - provide both electrical and biomechanical functional information
  - can simulate electrical and mechanical pathologies and specific surgery

Pluridisciplinary project

- ICEMA
  - INRIA:Caiman, Epidaure, Macs, Sinus, Sosso
  - Philips, King’s College (D. Hill)
- Following the pioneering work of
  - Mc Culloch et al.,
  - Mc Veigh et al.,
  - Papademetris, Sinusas, Duncan et al.,
  - P. Hunter, Young et al., ...

Myocardium Properties

The myocardium is composed of muscle fibre bundles:

It is an active non-linear viscoelastic anisotropic incompressible material.
Excitation-contraction coupling

<table>
<thead>
<tr>
<th>Scale</th>
<th>System</th>
<th>Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nano</td>
<td>molecular motors</td>
<td>Calcium ions</td>
</tr>
<tr>
<td></td>
<td>Langevin equations (SDE)</td>
<td>still to be designed</td>
</tr>
<tr>
<td>Micro</td>
<td>sarcomeres</td>
<td>ionic currents</td>
</tr>
<tr>
<td></td>
<td>Huxley-like models (PDE)</td>
<td>Luo-Rudy-like models</td>
</tr>
<tr>
<td>Meso</td>
<td>myocytes</td>
<td>action potential</td>
</tr>
<tr>
<td></td>
<td>BCS model (ODE)</td>
<td>FHN-like models</td>
</tr>
<tr>
<td>Macro</td>
<td>myocardium dynamics</td>
<td>action potential</td>
</tr>
<tr>
<td></td>
<td>equations</td>
<td>FHN-like models</td>
</tr>
<tr>
<td></td>
<td>(PDE with BCS Constitutive Law)</td>
<td>(PDE)</td>
</tr>
</tbody>
</table>

From Bestel-Clément-Sorine, MICCAI’01

---

Overview

- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction
- Conclusion

---

Geometry of Anatomy

- Segmentation of the Visible Human
  (courtesy of Pr Hoehne et al., Hamburg University)

---

Fiber Directions

- From diffusion tensor MRI (canine heart)
  (Dr. Hsu et al., Duke University)

---

Final Geometrical Model

- Purkinje network
  - LV and RV endocardium
  - from Durrer, D., van Dam, R. B., Freud, G.-E., Israel, M., Weijer, F. L., and

- Fixed areas (B. C.)
  - around the valves

---

Overview

- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction
- Conclusion
Electrical Model

- Action potential $u$ computation: 2 variables
- FitzHugh-Nagumo Reaction-Diffusion system

$$\frac{\partial u}{\partial t} = \text{div}(D \nabla u) + f(u) - z$$

$$\frac{\partial z}{\partial t} = b(u - cz)$$

$u$: action potential
$D$: diffusion tensor
$f$: ionic current
$z$: repolarization variable
$b$: repolarisation rate
$c$: repolarisation decay


Electrical Model Simulation

Isotropic Diffusion Tensor

$$D = \begin{bmatrix}
1 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}$$

Anisotropic Diffusion Tensor

$$D = \begin{bmatrix}
1 & 0 & 0 \\
0 & 0.8 & 0 \\
0 & 0 & 0.8
\end{bmatrix}$$

Electrical Simulation

Anisotropic model (fiber geometry + Purkinje network)

Comparison with Physiome Project

http://www.physiome.org/
ICEMA at INRIA

Comparison of Isochrones

Durrer et al.
ICEMA at INRIA

Overview

- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction
- Conclusion
Electro-Mechanical Coupling

• The myocardium muscle can be modelled from the Hill-Maxwell rheological law:

\[ E_s \text{ series element} \]
\[ E_p \text{ parallel element} \]
\[ E_c \text{ contractile element} \]
\[ u \text{ action potential} \]
\[ s \text{ stress} \]
\[ e \text{ strain} \]

• \( E_s \) and \( E_p \): elastic material laws.
• \( E_c \): contractile electrically-activated element.


Electro-Mechanical coupling

• Action potential \( u \) controls the contractile element:
  \[ u > 0 : \text{Contraction} \]
  \[ u < 0 : \text{Relaxation} \]
• \( u \) also modifies stiffness \( k \) of the material.

Contractile Element

• This electro-mechanical coupling system is derived from nano to mesoscopic scale:

\[
\frac{d k_c}{d t} = \left[ \frac{d k_c}{d t} \right] \left[ k + k_c \right] + u \frac{d e_c}{d t} + \sigma_c \frac{d e_c}{d t}
\]

\[
\frac{d e_c}{d t} = \left[ \frac{d e_c}{d t} \right] \left[ k + k_c \right] + u \frac{d k_c}{d t} + \sigma_c \frac{d k_c}{d t}
\]


Simplified Electro-Mechanical Coupling

• Piecewise linear viscoelastic anisotropic material

\[
\frac{d \sigma_c}{d t} = - \left[ \sigma_c + \sigma_0 \right] \left[ u \right]
\]

Only electrical command on contraction stress \( \sigma_c \)

Simplified Contraction Stress \( \sigma_c \)

\[
\frac{d \sigma_c}{d t} = - \left[ u \sigma_c + \sigma_0 \right] u
\]

\( u > 0 : \text{Contraction} \)
\( u < 0 : \text{Relaxation} \)

Numerical Computation

• Finite Element Method with linear tetrahedral element and transverse anisotropy.

\[
m \dddot{X} + \gamma \ddot{X} + \kappa X - F = 0
\]

\( m \): mass
\( X \): point position
\( \gamma \): damping
\( \kappa \): stiffness
\( F \): contraction forces

• Explicit or semi-implicit time integration
Contraction Results

\[ m \dddot{X} + \gamma \ddot{X} + KX = F \]

Endocardium surface

Boundary conditions: Vertices near the valves are fixed.

Overview

- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction (in progress)
- Conclusion

Introduction of Image Forces

\[ m \dddot{X} + \gamma \ddot{X} + KX = F_i + F_c \]

- \( F_i \) : Image Force: each model node is attracted towards most "plausible" image match.
- \( F_c \) : Contraction force in fiber direction
- Model can evolve under action of \( F_c \) or \( F_i \) independently
- Will evolve under simultaneous action of both forces (still work in progress)

Initialization: Generic Heart model fitted to specific MRI

Hierarchical Geometrical Matching

Tracking Gated MRI

Biomechanical model, image forces \( F_i \) only (\( F_c = 0 \))

Tracking Gated SPECT

Biomechanical model, image forces \( F_i \) only (\( F_c = 0 \))
Tracking Gated Spect
Biomechanical model, image forces $F_i$ only ($F_c = 0$)

Combining Image and Contraction Forces
- Requires additional data
- D. Hill et al., Electrical measurements and tagged MRI in the same heart, work in progress
- E. McVeigh et al., Measurement of ventricular wall motion, epicardial electrical mapping and myocardial fiber angles in the same heart, in FIMH’01, 2001.
- First experiments planned by the end of 2002

Simulating RF Ablation
- Collaboration with D. Hill (King’s College)
- Simulate electrical pathologies like fibrillation, arrhythmia, reentry, and radiofrequency surgery

Overview
- Motivation
- Anatomical Model
- Electrical Model
- Mechanical Coupling
- Cardiac Image Interaction
- Conclusion

Summary
- From Geometric to Passive and Active Biomechanical Models
- A simplified electro-mechanical model of the heart controlled through ECG and 4-D images
- Current development allows independent electro-mechanical simulation or image tracking. Coupling to be integrated soon!

Credits & References
- M. Sermesant, H. Delingette, N.A, Y. Coudière, J.A Desideri. An Electro-Mechanical Model of the Heart for Cardiac Image Analysis, MICCAI’01 (+Update at ISBI’02).
- N. Ayache, D. Chapelle, F. Clément, Y. Coudère, H. Delingette, J.A. Désidéri, M. Sermesant, M. Sorine and J. Urquiza. Towards Model-Based estimation of the cardiac electro-mechanical activity from ECG signals and ultrasound images, FIMH’01